The geoengineering approach to the study of rivers and reservoirs

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Abstract: This Special Publication contains contributions for two meetings held to explore the links between geoscience and engineering in rivers and reservoirs (surface and subsurface). The first meeting was held in Brazil and, as a result, the volume contains many contributions from Brazil. The second was held in Edinburgh, and produced contributions from modern rivers in the USA, China, India and Scotland. The geological record from Carboniferous to Recent is represented. A range of outcrop techniques are presented along with statistical techniques used to identify patterns in the time series and spatial sense. The book is intended to cover the cross-disciplinary interest in rivers and their sediments, and will interest geologists, geomorphologists, civil, geotechnical and petroleum engineers, and government agencies. Some of the papers collected here demonstrate longer term impacts of human activity on rivers and how these might change the future geological record and, more importantly in the short term, impact on the UN Global Sustainability Goals.

This Special Publication brings together a number of papers from two workshops held under the theme 'Rain, Rivers, Reservoirs' which considered the dynamic changes to river systems as part of natural processes but in particular under changing climatic conditions. The first of these was held in Brazil in

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2015. The Geological Society of London held the second workshop as part of the Geological Society's 2016 Year of Water events undertaken to promote 'debate of current research … on how the planet works and how we can live sustainably on it'. This volume compiles papers and abstracts presented in both workshops.

These workshops brought together scientists working from very short engineering timescales to long geological timescales, with the focus on understanding key controls on river behaviour and the resulting deposits. Combining the study of ancient analogue systems with modern-day processes gives a greater awareness of the impact that longer-term boundary conditions play on the modelling and prediction of fluvial systems, their role as stores, and their geological products. Engineers and geologists currently work at different scales and different time steps, and this introduction will highlight these aspects and help to inform future hydrologists, hydrogeologists, geologists and civil engineers in addressing the Sustainable Development Goals set by the United Nations to challenge traditional thinking. Initiatives such as Water and the Energy Industry (Simmons 2015) encourage participation from the water and traditional subsurface energy industries in addressing these goals – rivers and reservoirs and their interplay is the focus of this contribution.

The Geological Society's Special Publications have a long track record of compilations of research developments in fluvial systems. The economic importance of fluvial sedimentology was included in the early Volume 18 (Brenchley & Williams 1985) and followed up with a focus on the downstream deltaic portion of the system in Volume 41 (Whateley & Pickering 1989), driven by the discovery of major oil reserves in the Brent Group reservoirs of the North Sea celebrated in Volume 61 (Morton *et al.* 1992). The complexity of fluvial reservoirs was recognized by reservoir geologists in Volume 63 (Ashton 1993) and was the subject of a key Volume 75 on the specific issues in braided fluvial systems (Best & Bristow 1993). The interdisciplinary approach to the floodplain was the subject of Volume 163 (Marriot & Alexander 1999). The importance of fluvial reservoir architecture on reservoir compartmentalization was included in Volume 347 (Jolley *et al.* 2010), with a focus on geometry and heterogeneity in Volume 387 (Martinius *et al.* 2014). Increasing interest in off-planet fluvial systems resulted in Volume 440 (Ventra & Clarke 2018). These volumes chart the developing research and approaches in rivers, their sediments, and the resulting complex reservoirs. This current volume is essentially an update on progress since volumes 75 and 163 and brings together rivers and reservoirs with a global cross-disciplinary perspective. Because of the initial workshop, this volume brings together a strong Brazilian component.

This volume has been arranged in a geoengineering framework, collected into three broad sections – Architecture and properties; Modelling and simulation; and Management – as used in subsurface studies linking geoscience and engineering (Corbett 2009). In this way, we have tried to avoid the geologist v. engineer split of working practices that seems to exist (from what folk say anyway in the study of hydrology and hydrogeology (Helen Reeves pers. comm.), and we can all find our own anecdotal evidence). Multidisciplinary working is very much the way in which the UN Global Challenges will need to be tackled and this book hopes to stimulate such cross-disciplinary interests.

Architecture and properties

In this section a number of studies on modern systems (**Blum 2019**; Sinclair *et al.* 2016; **Nicholson *et al.* 2019**) are compared with ancient counterparts, from the Cenozoic (Stow *et al.* 2016) and Mesozoic (**Dal' Bó *et al.* 2018**; **Yeste *et al.* 2018**; **Fambrini *et al.* 2019**) through to the Paleozoic (Reesink 2016; **Ellen *et al.* 2018**). In reconciling these two timescales, it is necessary to find common ground between studies which focus on the plan-view (top-down) evolution of fluvial systems (often the focus of modern studies) and the cross-sectional view often employed by studies of ancient relict landforms in the geological record.

One such approach is through the understanding of bedform evolution (**Best & Fielding 2019**). A more detailed understanding of the properties – characteristics of lithologies, sedimentary structures linked to the depositional architecture – of modern braided, meandering and anastomosing rivers, allows information from the geological record to be inferred. Conversely, by studying the preserved bedforms in the geological record, we may critically evaluate our current thinking and models of multichannel river systems. **Best & Fielding (2019)** examine dune bedforms, perhaps the dominant small-scale alluvial bedform across a wide range of large alluvial channels, and show their morphology, and especially their leeside angle, to be very different to classic angle-of-repose dunes. They provide a unique dataset that quantifies these characteristics, which is used to discuss possible controls on such dune morphology. In particular, they focus on what we might expect to see when examining such bedforms in the ancient sedimentary record and the implications of these characteristics for flow-depth reconstruction from cross-set thickness. Very-low-angle, almost horizontal, laminae are characteristic of lee slopes in mixed-load rivers, and bedform stability diagrams will require modifications to take into account the influence of fines on the bedform angle. Reesink (2016) highlighted the lack of fines in most pre-vegetation fluvial systems, and noted that such systems may have different geobody geometries and structures as a result of the lack of clay, but also that they may, in some cases, have a strong microbial influence instead. The alluvial architecture of the Río Bermejo River in Argentina is considered a highly active meandering river that transports a large fine-grained sediment load. **Best & Fielding (2019)** contribute their thoughts on the current distributive fluvial system model debate (Weissmann *et al.* 2010; Owen *et al.* 2015, 2016, 2017; Hartley *et al.* 2016) with a call for linking short-term processes with consideration of longer-term processes in modern systems. They caution the reader against overuse of planform geometry in isolation of wider considerations. The importance of storey surfaces in the sectional view is noted (Owen *et al.* 2017).

Continuing a focus on the world's largest rivers as unique analogues for geological records, **Blum (2019)** considers how the Mississippi drainage system has organized and reorganized itself through time. The Holocene–modern Mississippi delta was constructed by aggradation and progradation over a period of 7000 years, as global sea-level rise decelerated and reached the present highstand positions. Land gain and land loss is natural in deltaic systems, but loss rates accelerated in the last century due to: (a) an acceleration of global sea-level rise; (b) dam construction that reduced sediment load (supply limited); and (c) a continuous levee system that limits dispersal to the delta plain (transport-limited). More than 11 000 km^2 of the Mississippi delta region is less than 0.5 m in elevation, and will be likely to drown by 2100 – there is only enough sediment to sustain <25% of the delta surface area.

The Colorado River in the SW USA is one of the Earth's few continental-scale rivers with an active margin delta (**Nicholson *et al.* 2019**). Deformation along this transform margin, as well as associated intra-plate strain, has resulted in significant changes in sediment routing from the continental interior and post-depositional translation of older deltaic units. The oldest delta candidate deposits, fluvial sandstones of the Eocene Sespe Formation, are now exposed in the Santa Monica Mountains, 300 km to the north of the modern-day Colorado. Sedimentological and mineralogical evidence from the earliest (*c.* 5.3 Ma) unequivocal Colorado-River-derived sediments in the Salton Trough provide evidence for a rapid transition from locally derived sedimentation. Lack of evidence for a precursor phase of suspended-load sediment suggests that drainage capture took place in a proximal position, favouring a 'top-down' process of lake spillover. Following drainage integration, significant changes in detrital mineralogy of fluvio-deltaic sediments document the progressive incision of strata from the Colorado Plateau from the Miocene to the present. The Colorado is an example of a river responding to major long-term and dramatic disruptions to the boundary conditions (sink changing from a convergent margin to a transform margin, opening of the Gulf of California, climate changes during the Miocene) with significant implications for the morphology and sedimentation. The paper on the Nheocolândia wetlands in central Brazil (**Oliveira *et al.* 2018**) presents a unique insight into a modern intra-continental fluvial environment where human interaction and climate impact are closely related. Formed of thousands of distinct saline and non-saline lakes, the Nhecolândia region is unique in its modern hydrological regime. Insight into the intrinsic linkages between this unique wetland hydrology, the associated ecosystems provision, and the potential for land-use and climate change is provided by **Oliveira *et al.* (2018)**. This paper demonstrates the potentially significant impacts that small changes in the water supply as a result of future climate or land-use change may play on the region compared to the major changes seen to the Colorado over its lifetime.

Traditionally, studies of distributive fluvial systems rely primarily on understanding the stacking of architectural elements in space, controlled by the radial distribution of channels away from an apex or apices located at the basin margin (Weissmann *et al.* 2010). This approach centres on the downstream dynamics of the fluvial network. In order to understand the vertical dynamics and organization of distributive fluvial systems, **Dal' Bó *et al.* (2018)** analysed deposits from the proximal part of a distributive fluvial system from the NE margin of the Bauru Basin (Upper Cretaceous, SE Brazil). The fluvial succession records the deposition of a semi-arid distributive fluvial system, enabling understanding of the vertical dynamics of channels and associated floodplain deposits in these systems. The stratigraphic alternation between channel types of drier and more humid climatic regimes has revealed high-frequency climate-induced cycles influencing the organization of the fluvial deposits. Furthermore, palaeosols, which constitute the stratigraphic boundaries of the studied succession, reveal a superimposed longer-term geomorphological cycle marking variations in the recurrence time of avulsions of the channel system. This work describes how climatic and geomorphological factors act together as the most likely controlling mechanisms for the vertical organization of this distributive fluvial system. Calcrete development in the system can provide a strong restriction to vertical permeability in a reservoir context.

Fambrini *et al.* (2019) describe how the Barbalha Formation (Aptian) represents the initial sedimentary record of the post-rift stage of the Araripe Basin, NE Brazil, which consists predominantly of sandy fluvial facies with reddish and yellowish pelitic intercalations and thin layers of conglomerates and lacustrine bituminous black shales. This study differentiates two main fluvial sequences, separated by lacustrine bituminous shales. The first is represented by a braided-style fluvial association constituted of orange-yellow, micaceous, friable, coarse to fine sandstones, with planar and trough cross-stratifications, and thin layers of fine conglomerates, and by interlaminations of shales and mudstones. The upper sequence represents a meandering-tyle fluvial association that is also sandy, but with disseminated mudstones and shales. It consists of thin sandstones of yellowish to grey colour, and reddish mudstones and siltstones and greyish to black shales deposited under low-energy conditions. Conglomeratic facies tend to be thin and the sequence fines upwards. At the base of the second sequence there is the occurrence of thin conglomerates, denoting an erosive unconformity. The interpretation of these sequences is primarily a braided continental fluvial system resulting from tectonic subsidence due to post-rift reactivation of faults with close association with a lacustrine basin. Other Cretaceous fluvial sandstones in the São Sebastião Formation and the Marizal Formation (Tucano Basin) in NE Brazil have also been subject to reservoir characterization studies (Carrera 2015; Janikian 2015).

A Triassic sandstone geobody has been studied by **Yeste *et al.* (2018)** from the Triassic red beds of the Iberian Meseta (TIBEM) Formation in south-central Spain and interpreted to record the sedimentary dynamics of a fluvial braidplain. This particular example has been highlighted in the literature as an outstanding outcrop analogue for productive reservoirs such as the Algerian TAGI (Trias Argilo-Gréseux Inférieur) (**Yeste *et al.* 2018**). The analysis of architectural elements in outcrop allows differentiation of the sub-environments of deep perennial channel, compound bar, cross-bar channel and bar tail elements. Of the total geobody population, 80% is represented by sandy compound bars up to 1000 m long and 500 m wide, developed in four building phases. At the base, each compound bar starts with a thick set of planar cross-stratification corresponding to a transverse unit bar. On top of this, several thinning-upwards sets of planar and trough cross-bedding suggest that the subaerial accommodation space progressively decreased to become an island of rippled sands with clay and silt layers intercalated. Petrophysical analysis shows that lithofacies association within each sub-environment constitutes the main control on permeability baffle distribution throughout this reservoir analogue. The occurrence of clay drapes within the compound bars will have a significant impact on the vertical permeability (as also noted by **Best & Fielding 2019**). This study incorporates a range of techniques to aid the 3D investigation. A total of six wells, with core recovery and well-logging (natural and spectral gamma ray, optical and acoustic televiewer) data acquisition, have been drilled behind the outcrop targeting the main sub-environments. The combination of these subsurface data with the Georadar Survey and their comparison with the outcrop analysis has allowed the development of stochastic and deterministic models that accurately reproduce the distribution of reservoir heterogeneities. These models show a significant lateral variability within a laterally extensive, 17 m-thick, sheet-like system, which can then be used to improve operational strategies during enhanced oil recovery performances in this type of fluvial reservoirs.

Ellen *et al.* (2018) describe in detail an outcrop of Lower Carboniferous fluvial sandstones from SW Scotland. The Spireslack surface coal mine offers outstanding, national to international standard, nearly complete exposure from the Lawmuir Formation (Brigantian) through to most of the Upper Limestone Formation (Arnsbergian). It shows all the nationally recognized marine limestones and marine bands up to and including the Calmy Limestone. It is the most continuous Mississippian Sub-Period section in Scotland and also in the Muirkirk (East Ayrshire) Coalfield basin, where it also provides a reference section for the locally named coal and ironstone seams. Relationships between the architecture of the large fluvial sand bodies within this stratigraphic framework are described. Two sandstone bodies are interpreted as being deposited in a low-sinuosity sand-dominated palaeovalley of significant relief. This setting could provide an analogue for a more restricted, stratigraphically-isolated, incised, reservoir trapping system. The outcrop also shows an interaction of the sedimentary response to syndepositional tectonic activity; features (if present in the subsurface) that will only add to reservoir complexity and potential compartmentalization.

Modelling and simulation

In the previous section a number of authors generated 2D panels (Stow *et al.* 2016; **Fambrini *et al.* 2019**) and developed 3D reconstructions of outcrop architecture (**Ellen *et al.* 2018**; **Yeste *et al.* 2018**). These models and the data collected in the field can be used for training images and statistical datasets for the building of 3D reservoir models (Martinius *et al.* 2014; Beaumont *et al.* 2016). Models of fluvial systems for the purpose of simulation are often geostatistical through to finite difference/finite element. Stochastic modelling is used in hydrology

(**Patidar *et al.* 2018**) to constrain 2D simulations (Xia & Liang 2016) and 3D simulations (Wang 2016) depending on the complexity of the problem. Machine learning from Google Earth images (Ahmed *et al.* 2016; Russell *et al.* 2016) through to core datasets (**Demyanov *et al.* 2019**) can help to quantify uncertainty and improve geological classifications. Understanding 3D responses in the subsurface can utilize valuable engineering data in support of the geological models (**Corbett & Duarte 2018**). The interaction between understanding of the process, relating it to geology, collecting quantitative data and building 3D models for simulation is important in the understanding of preserved fluvial systems. Statistical analysis of modern rivers might assist in the development of more process-based models which can also improve the workflow.

In recent years, the application of machine learning and statistical techniques has improved our ability to forecast and predict extreme behaviour in natural systems. A range of mathematical tools and software, mainly based on the use of a single *N* year extreme flow or rainfall event, are available to conduct a thorough assessment of fluvial flood risk and various related aspects of flood risk management (FRM) projects. Utilizing multiple realizations of flow sequences can assure a robust approach for attaining long-term sustainability of FRM projects. Previous studies have been shown to generate reliable results (multiple realizations of daily streamflow sequences) through successful application of stochastic modelling approaches such as the hidden Markov model (HMM) coupled with the generalized extreme value distribution (HMM-GEV) and generalized Pareto (HMM-GP) distribution. The HMM-GP model has been rigorously accessed for its ability for capturing the various statistical characteristics and stochasticity of the simulated flow sequences. Models have been robustly validated across four hydrologically distinct catchments in the UK (the rivers Don, Nith, Dee and Tweed) and demonstrate excellent performance (**Patidar *et al.* 2018**). These models might be further extended from civil engineering into the geological domain, to run at geological timescales with changing boundary conditions as a result of base level (either climatic or tectonic or both) variations and history-matched with geological systems.

Demyanov *et al.* (2019) apply machine-learning techniques to objectively classify the information encapsulated in sedimentary logs from two modern braided rivers: the Río Paraná in Argentina and the South Saskatchewan River in Canada. They apply various data-classification techniques, such as self-organizing maps, for unsupervised clustering of sedimentary logs. Early results show that machine-learning classification has indeed the potential to reveal interpretable sedimentological information by grouping well logs according to consistent sedimentological patterns. A statistical framework for interpretation of such data (even if these are expert interpretations) might enable the calibration of models back to at least recent geological time. These data-mining approaches could then be applied to older and more complex systems.

Extending the modelling of physical processes and responses from the Earth's surface into the subsurface could yield particularly useful results in the future. Translating what is visible in a vertical well profile to what is happening laterally at inter-well distances in fluvial reservoirs and aquifers is a challenge facing the subsurface community exploring ancient fluvial systems (**Corbett & Duarte 2018**). Producing fluids from a well and then shutting it in and observing the pressure build-up provides a signal from the near-wellbore region. Interpretation of that build-up response in fluvial reservoirs can be challenging as the response is most sensitive to the highest permeability regions connected to the wellbore. Fluvial reservoir rocks have some of the most variable, composite architectural arrangements leading to a myriad of pressure responses. What the pressure 'sees' – or responds to – in 3D is very difficult for geologists and engineers to easily comprehend (often because of a common language). At the present time, engineers have no single analytical model to cover the myriad of fluvial reservoir pressure responses. 'End-point' relatively simple models exist. Complex geological models can be built from detailed Google Earth images, as can be seen in the case study from Colombia. Exploration of the possible responses by geo/flow modelling and comparison of synthetic geotype curves with real build-up data can help to constrain the more appropriate architectural scenarios. The clay drapes internal to the compound bars described by **Yeste *et al.* (2018)** and the calcretes described by **Dal' Bó *et al.* (2018)** will reduce vertical permeability – conditions whereby the lateral connectivity will become the critical aspect of pressure support. The model of **Yeste *et al.*** (**2018**, fig. 9) illustrates nicely the lateral stacking pattern implied by the well testing models. Further work is required to link the vertical and lateral stacking implied by the distributive fluvial model (A and C, B and D in Fig. 1) (Owen *et al.* 2017) with the Type I, II and III well test models (**Corbett & Duarte 2018**).

Management

Water supplies play into many of the key United Nation's Sustainable Development Goals (Fig. 2). In securing water supplies, **Blum (2019)** shows how trapping sediment in the dams along the Mississippi has reduced the dominance of the river and influenced the downstream 'health' of the delta. Management of water through periods of drought

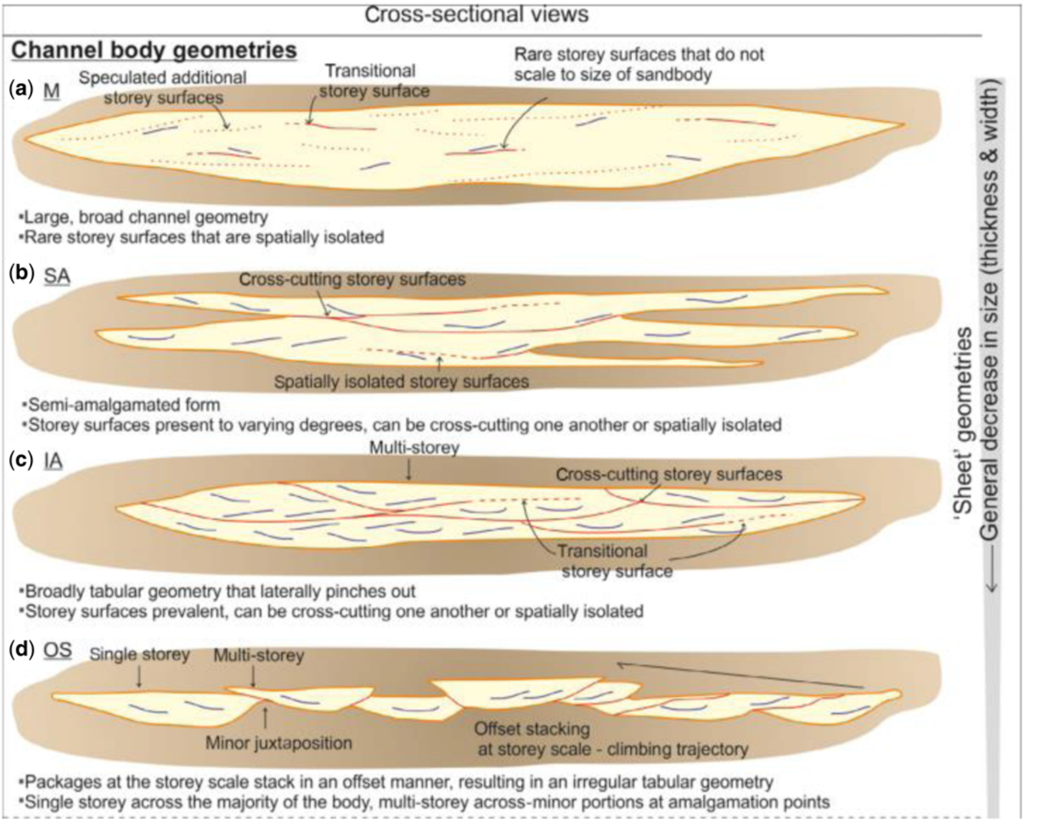

Fig. 1. Cross-sectional views of the distributive fluvial system (reproduced from Owen *et al.* 2017) showing the importance of transitional and cross-cutting storey surfaces along within multi-storey fluvial systems.

or flooding (Germano & Castilho 2016) is a major challenge in a country such as Brazil (**Kuwajima *et al.* 2019**). How will longer-term climate trends (from climate models) deal with the likelihood of increasing extreme events? What can the geological record tell the forecasters? The Nheocolândia wetlands in central Brazil (**Oliveira *et al.* 2018**) present a unique insight to an intra-continental fluvial environment where regional rainfall and regional-scale climatic cycles control the water regimes in this semi-arid region. Small changes in water sources in this delicate location can have large changes that impact society at a much larger scale. The history of changes along major river courses reflects the impact mankind has had on rivers over short timescales (Skelton 2015) overprinted on longer timescale palaeoclimatic changes (Hill 2015).

An effective water resource management strategy is important to meet multiple objectives such as water supply, navigation, hydroelectricity generation, environmental obligations and flood protection. By implementing a predictive control approach over a short-term forecast horizon, it is possible to foresee stress conditions or peak flow events and support decision-makers to take action before these events happen, thus minimizing their impacts. In the case of flood events, this technique enables the operators to pre-release water from a reservoir to allocate additional storage before the flood event occurs in order to mitigate flood damage along downstream river reaches. A scenario that would have prevented the flooding of housing stock during Hurricane Harvey in the Greater Houston area in August 2017. For that purpose, a robust and fast routing model is required in order to obtain quick and reliable estimates of downstream flow conditions related to release changes of the reservoir. The novel short-term optimization approach consists of the reduction of ensemble forecasts into scenario trees as an input into a multi-stage stochastic optimization (**Kuwajima *et al.* 2019**).

The damming of the San Sabastian River, the subject of water management strategies (Silva 2015), in NE Brazil which caused a rise in water level and flooding of a fluvial system presents an interesting analogue of the effect of rising sea level

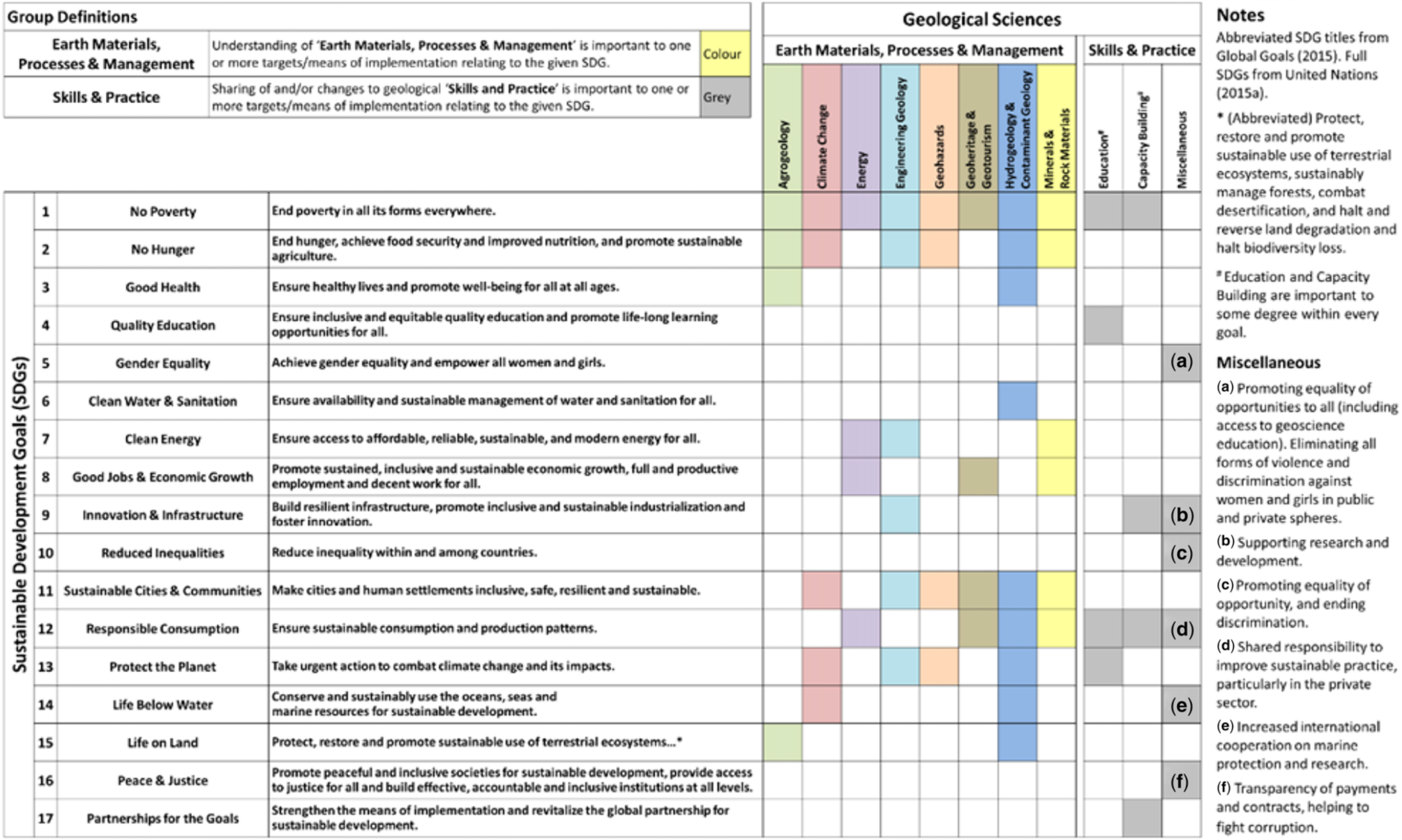

Fig. 2. A matrix showing the role of geologists in helping to achieve the UN's Global Sustainability Development Goals (Gill & Smith 2017).

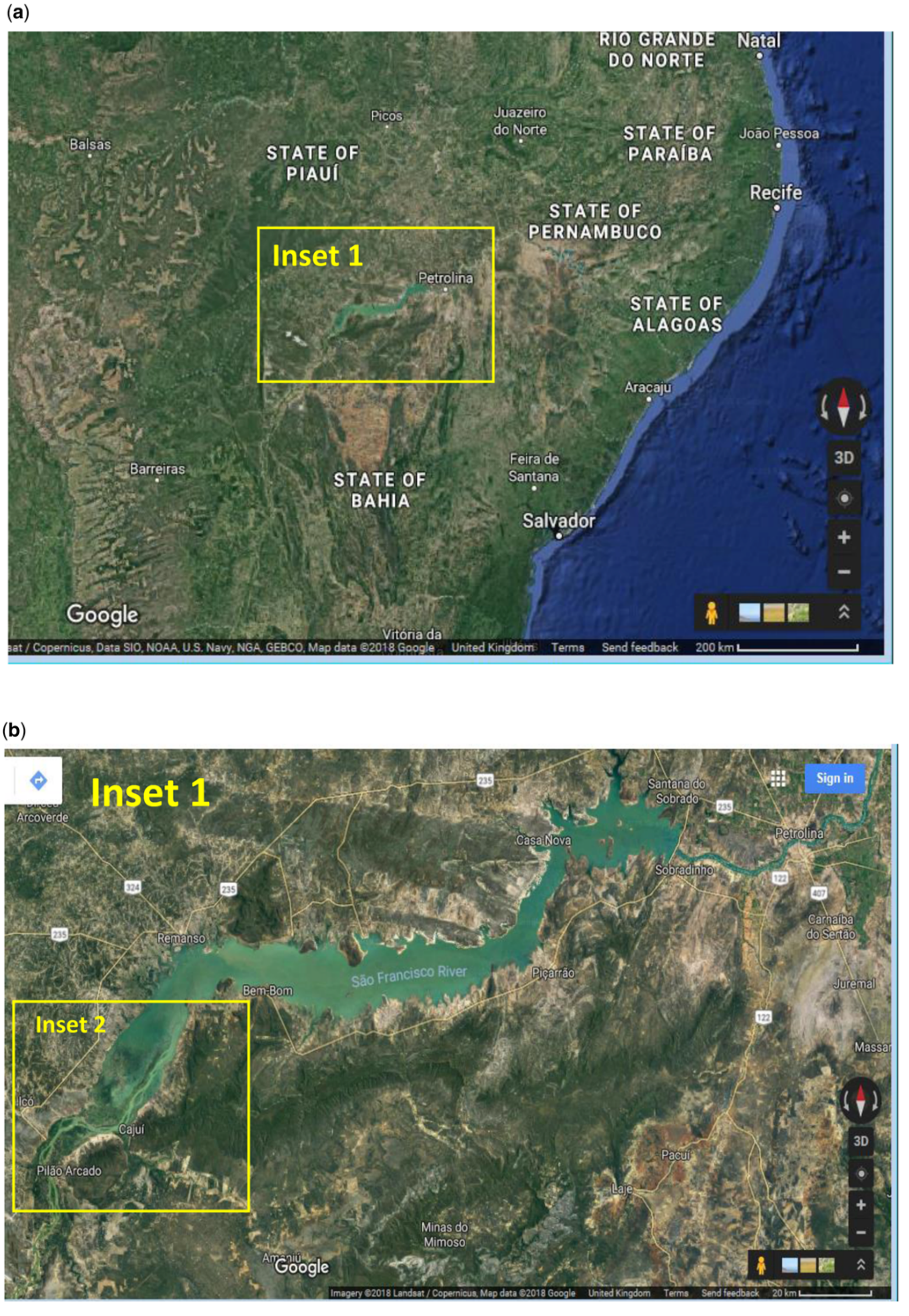

Fig. 3. The drowning of the San Sebastian River system, NE Brazil, by the Largo Sobradinho as a result of a dam being built provides a small-scale analogue to the processes seen in fluvial systems due to rising sea levels and illustrates the various aspects of changing river systems addressed in this volume (© 2018 Google Earth CNES/ Airbus). The largest field of view is 1000 × 600 km, the smallest is 40 × 30 km.

(c)

Fig. 3. *Continued.*

on coastal systems (Fig. 3). The same situation occurs in the Mississippi (**Blum 2019**) and all other rivers where artificial reservoirs trap sediment. Monsoons can also wreak havoc on fluvial systems in coastal tropical areas (Hackney 2016).

Water resource management is one of the greatest threats facing many communities in the face of changing climates and increased demand. Hedging (the holding back of water for drier periods) is universally recognized as a useful practice for redistributing water shortages to avoid occasions of large, crippling water shortages during surface water reservoir operation (**Adeloye & Soundharajan 2018**). However, when based on zones of available reservoir storage, hedging has traditionally been static in that the rationing ratio (i.e. the supply/demand ratio) is constant from one period to another. Given the seasonal variations in inflows into reservoirs, it should be expected that certain periods or months in the year should require less hedging and, hence, be able to supply more water than others, thus further enhancing the effectiveness of hedging as a systems performance enhancer. In this study, **Adeloye & Soundharajan (2018)** examine the effect of dynamically varying hedging policies on the performance of the Pong reservoir on the Beas River in Himachal Pradesh, India. The impact on aquifers in Brazil is also a significant water resource issue (Hirato *et al.* 2015). The geotechnical interaction of water in the soil (Barreto 2015) impacts water run-off and storage, as well as slope stability. Civil engineering models are able to simulate the processes (Fan 2015; Guan 2016; Liang 2016).

Statistical models can take data over limited time periods at high resolution and extrapolate to longer periods, such as the study on various Scottish rivers described in this volume (**Patidar *et al.* 2018**). These models can be further constrained by longer-term climate and usage changes (Fan 2015).

There is also a role for government and government agencies in managing water resources (Jenkins 2015; Reeves *et al.* 2015) in the face of the challenges mentioned, and this volume might encourage a more holistic approach to scientific study to meet society's needs.

Concluding remarks

This volume is intentionally ambitious in spread and has pulled together a wide range of contributions across the geoscientific and civil engineering domains. These domains are normally conventionally addressed in single, separate, volumes. The reader can select the part of the domain of most interest and absorb related issues for closely related domains. The importance to, and interest of, governing and government agencies is highlighted.

Understanding the context of fluvial models continues to dominate the geological literature, with the impact of the more recent distributive fluvial systems model building on older braided/meandering/anastomosing models; and both are used in this volume. Emphasis on the knowledge of the processes of deposition, evolving three-dimensional architectural models, will help in the interpretation of sparse subsurface records.

Useful outcrop-based sand-body descriptions with channel dimensions and stacking patterns, with compound bars, associated calcretes and clay drapes, are presented from the Carboniferous to Recent. These are of interest to the subsurface reservoir characterization community. Subsurface 3D modelling has proven the importance of lateral and vertical connectivity (the former controlled by lateral amalgamation and the latter controlled by clay drapes, calcretes, and more general intercalated floodplain deposits).

The impact of modern rivers on society is immense and climate change will doubtless change the geomorphology of rivers, as it has done in the past. Understanding the context of palaeorivers will potentially improve the understanding of how our modern rivers will change. For certain systems, tectonic controls exert an equally strong or even stronger control on the river systems than glacio-eustatic climate change drivers.

A full range of modern data-mining techniques will surely be deployed to Google Earth images, ancient geological records and modern river data to improve the statistical characterization and modelling of fluvial systems and uncertainty predictions thereof.

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References

Adeloye, A.J. & Soundharajan, B.-S. 2018. Effect of dynamically varying zone-based hedging policies on the operational performance surface water reservoirs during climate change. *In*: Corbett, P.W.M., Owen, A., Hartley, A.J., Pla-Pueyo, S., Barreto, D., Hackney, C. & Kape, S.J. (eds) *River to Reservoir: Geoscience to Engineering*. Geological Society, London, Special Publications, **488**. First published online December 17, 2018, https://doi.org/10.1144/SP488.1

Ahmed, J., Constantine, J.A. & Dunne, T. 2016. Sediment-triggered meander deformation in the Amazon Basin. Abstract presented at the Rain, Rivers, Reservoirs Geological Society Meeting, 27–30 September 2016, Edinburgh, UK, https://www.geolsoc.org.uk/~/media/shared/documents/Events/Past%20Meeting%20Resources/RRR%20conference/RRR%20abstract%20book.pdf

Ashton, M. (ed). 1993. *Advances in Reservoir Geology*. Geological Society, London, Special Publications, **69**, https://doi.org/10.1144/GSL.SP.1993.069.01.11

Barreto, D. 2015. Rain, rivers and reservoirs – a geotechnical perspective. Abstract presented at the 1st Rain, Rivers, Reservoirs Meeting, 1–3 September 2015, São Paulo, Brazil, available at https://researchportal.hw.ac.uk/en/publications/rain-rivers-reservoirs-conference-sao-paulo-brazil-abstract-bookl

Beaumont, H., Taylor, A., Clarke, S. & Mohapatra, P. 2016. Proximal outcrop to distal core deposits comparisons for the hydrocarbon industry: examples from the Barmer Basin. Abstract presented at the Rain, Rivers and Reservoirs Geological Society Meeting, 27–30 September 2016, Edinburgh, UK, https://geolsoc.org.uk/~/media/shared/documents/Events/Past%20Meeting%20Resources/RRR%20conference/RRR%20abstract%20book.pdf

Best, J. & Fielding, C.R. 2019. Describing fluvial systems: linking process to deposits and stratigraphy. *In*: Corbett, P.W.M., Owen, A., Hartley, A.J., Pla-Pueyo, S., Barreto, D., Hackney, C. & Kape, S.J. (eds) *River and Reservoir: Geoscience to Engineering*. Geological Society, London, Special Publications, **488**. First published online February 15, 2019, https://doi.org/10.1144/SP488-2019-056

Best, J.L. & Bristow, C.S. (eds). 1993. *Braided Rivers*. Geological Society, London, Special Publications, **75**, https://doi.org/10.1144/GSL.SP.1993.075.01.24

Blum, M. 2019. Organization and reorganization of drainage and sediment routing through time: the Mississippi River system. *In*: Corbett, P.W.M., Owen, A., Hartley, A.J., Pla-Pueyo, S., Barreto, D., Hackney, C. & Kape, S.J. (eds) *River to Reservoir: Geoscience to Engineering*. Geological Society, London, Special Publications, **488**, https://doi.org/10.1144/SP488-2018-166

Brenchley, P.J. & Williams, B.P.J. (eds). 1985. *Sedimentology: Recent Developments and Applied Aspects*. Geological Society, London, Special Publications, **18**, https://doi.org/10.1144/GSL.SP.1985.018.01.01

Carrera, S. 2015. Alluvial/fluvial morphology and flooding/reservoir responses. Abstract presented at the 1st Rain, Rivers, Reservoirs Meeting, 1–3 September 2015, São Paulo, Brazil, available at http://www.pet.hw.ac.uk/lib/media/rrr/downloads/RRR_Workshop_Handout_Final.pdf

Corbett, P. 2009. *Petroleum Geoengineering: Integration of Static and Dynamic Models*. SEG/EAGE Distinguished Instructor Series, **12**. Society of Exploration Geophysicists, Tulsa, OK.

Corbett, P.W.M. & Duarte, G.L.B. 2018. Understanding subsurface fluvial architecture from a combination of geological well test models and well test data. *In*: Corbett, P.W.M., Owen, A., Hartley, A.J., Pla-Pueyo, S., Barreto, D., Hackney, C. & Kape, S.J. (eds) *River to Reservoir: Geoscience to Engineering*. Geological Society, London, Special Publications, **488**. First published online December 14, 2018, https://doi.org/10.1144/SP488.7

Dal' Bó, P.F., Soares, M.V.T., Basilici, G., Rodrigues, A.G. & Menezes, M.N. 2018. Spatial variations in distributive fluvial system architecture of the Upper Cretaceous Marília Formation, SE Brazil. *In*: Corbett, P.W.M., Owen, A., Hartley, A.J., Pla-Pueyo, S., Barreto, D., Hackney, C. & Kape, S.J. (eds) *River to Reservoir: Geoscience to Engineering*. Geological Society, London, Special Publications, **488**. First published online November 29, 2018, https://doi.org/10.1144/SP488.6

Demyanov, V., Reesink, A.J.H. & Arnold, D. 2019. Can machine learning reveal sedimentological patterns in river deposits? *In*: Corbett, P.W.M., Owen, A., Hartley, A.J., Pla-Pueyo, S., Barreto, D., Hackney, C. & Kape, S.J. (eds) *River to Reservoir: Geoscience to Engineering*. Geological Society, London, Special Publications, **488**, https://doi.org/10.1144/SP488-2018-84

Ellen, R., Browne, M.A.E., Mitten, A.J., Clarke, S.M., Leslie, A.G. & Callaghan, E. 2018. Sedimentology, architecture and depositional setting of the fluvial Spireslack Sandstone of the Midland Valley, Scotland: insights from Spireslack surface coal mine. *In*: Corbett, P.W.M., Owen, A., Hartley, A.J., Pla-Pueyo, S., Barreto, D., Hackney, C. & Kape, S.J. (eds) *River to Reservoir: Geoscience to Engineering*. Geological Society, London, Special Publications, **488**. First published online November 21, 2018, https://doi.org/10.1144/SP488.2

Fambrini, G.L., da Cunha Silvestre, D., de Menezes-Filho, J.A.B., da Costa, I.C. & de Miranda Lopes Neumann, V.H. 2019. Architectural and facies characterization of the Aptian fluvial Barbalha Formation, Araripe Basin, NE Brazil. *In*: Corbett, P.W.M., Owen, A., Hartley, A.J., Pla-Pueyo, S., Barreto, D., Hackney, C. & Kape, S.J. (eds) *River to Reservoir: Geoscience to Engineering*. Geological Society, London, Special Publications, **488**, https://doi.org/10.1144/SP488-2017-275

Fan, F.M. 2015. Ensemble hydrological forecasting for flood anticipation and reservoirs operation: Brazilian case studies. Abstract presented at the 1st Rain, Rivers and Reservoirs Meeting, 1–3 September 2015, São Paulo, Brazil, available at https://researchportal.hw.ac.uk/en/publications/rain-rivers-reservoirs-conference-sao-paulo-brazil-abstract-bookl

Germano, A. & Castilho, A. 2016. Learnings from Madeira River, Amazon region floods in 2014. Abstract presented at the Rain, Rivers and Reservoirs Geological Society Meeting, 27–30 September 2016, Edinburgh, UK, https://researchportal.hw.ac.uk/en/publications/rain-rivers-reservoirs-conference-sao-paulo-brazil-abstract-bookl

Gill, J.C. & Smith, M. 2017. Sustainable futures. *Geoscientist Online*, June, https://www.geolsoc.org.uk/Geoscientist/Archive/June-2017/Sustainable-futures

Guan, M. 2016. Modelling sediment transport and morphological change within flooding. Abstract presented at the Rain, Rivers, Reservoirs Geological Society Meeting, 27–30 September 2016, Edinburgh, UK, https://www.geolsoc.org.uk/~/media/shared/documents/Events/Past%20Meeting%20Resources/RRR%20conference/RRR%20abstract%20book.pdf

Hackney, C. 2016. Variability in monsoon strength recorded by crevasse-splay sedimentation of large river floodplains. Abstract presented at the Rain, Rivers and Reservoirs Geological Society Meeting, 27–30 September 2016, Edinburgh, UK, https://www.geolsoc.org.uk/~/media/shared/documents/Events/Past%20Meeting%20Resources/RRR%20conference/RRR%20abstract%20book.pdf

Hartley, A.J., Owen, A. & Weissmann, G.S. 2016. Using outcrop, subsurface and modern day analogues to predict basin-scale alluvial architecture. Abstract presented at the Rain, Rivers and Reservoirs Geological Society Meeting, 27–30 September 2016, Edinburgh, UK, https://www.geolsoc.org.uk/~/media/shared/documents/Events/Past%20Meeting%20Resources/RRR%20conference/RRR%20abstract%20book.pdf

Hill, D. 2015. Modelling the palaeoclimate of South America: Biosphere and hydrological response to Pliocene warming. Abstract presented at the 1st Rain, Rivers and Reservoirs Meeting, 1–3 September 2015, São Paulo, Brazil, available at https://researchportal.hw.ac.uk/en/publications/rain-rivers-reservoirs-conference-sao-paulo-brazil-abstract-bookl

Hirato, R., Franzen, M., Montenegro, S. & Petelet, E. 2015. Past and future climate evolution and its impact on aquifers of Recife, NE of Brazil. Abstract presented at the 1st Rain, Rivers and Reservoirs Meeting, 1–3 September 2015, São Paulo, Brazil, available at https://researchportal.hw.ac.uk/en/publications/rain-rivers-reservoirs-conference-sao-paulo-brazil-abstract-bookl

Janikian, L. 2015. Depositional architecture and outcrop-scale distribution of porosity and permeability in fluvial sandstones of the São Sebastião Formation (Early Cretaceous, Tucano Basin, NE Brazil). Abstract presented at the 1st Rain, Rivers and Reservoirs Meeting, 1–3 September 2015, São Paulo, Brazil, available at https://researchportal.hw.ac.uk/en/publications/rain-rivers-reservoirs-conference-sao-paulo-brazil-abstract-bookl

Jenkins, J. 2015. Towards a comparative understanding of government water problem-solving responses. Abstract presented at the 1st Rain, Rivers and Reservoirs Meeting, 1–3 September 2015, São Paulo, Brazil, available at https://researchportal.hw.ac.uk/en/publications/rain-rivers-reservoirs-conference-sao-paulo-brazil-abstract-bookl

Jolley, S.J., Fishers, Q.J., Ainsworth, R.B., Vrolijk, P.J. & Delisle, S. (eds). 2010. *Reservoir Compartmentalisation*. Geological Society, London, Special Publications, **347**, https://doi.org/10.1144/SP347.0

Kuwajima, J.I., Fan, F.M., Schwanenberg, D., dos Reis, A.A., Niemann, A. & Mauad, F.F. 2019. Climate change, water-related disasters, flood control and rainfall forecasting: a case study of the São Francisco River, Brazil. *In*: Corbett, P.W.M., Owen, A., Hartley, A.J., Pla-Pueyo, S., Barreto, D., Hackney, C. & Kape, S.J. (eds) *River to Reservoir: Geoscience to Engineering*. Geological Society, London, Special Publications, **488**. First published online April 9, 2019, https://doi.org/10.1144/SP488-2018-128

Liang, Q. 2016. The development of next generation of multi-purpose modelling system for flood risk management. Abstract presented at the Rain, Rivers and Reservoirs Geological Society Meeting, 27–30 September

2016, Edinburgh, UK, https://www.geolsoc.org.uk/~/media/shared/documents/Events/Past%20Meeting%20Resources/RRR%20conference/RRR%20abstract%20book.pdf

Marriot, S.B. & Alexander, J. (eds). 1999. *Floodplains: Interdisciplinary Approaches*. Geological Society, London, Special Publications, **163**, https://doi.org/10.1144/GSL.SP.1999.163.01.25

Martinius, A., Howell, J.A. & Good, T.R. (eds). 2014. *Sediment-Body Geometry and Heterogeneity: Analogue Studies for Modelling the Subsurface*. Geological Society, London, Special Publications, **387**, https://doi.org/10.1144/SP387.0

Morton, A.C., Haszeldine, R.S., Giles, M.R. & Brown, S. (eds). 1992. *Geology of the Brent Group*. Geological Society, London, Special Publications, **61**, https://doi.org/10.1144/GSL.SP.1992.061.01.25

Nicholson, U., Carter, A., Robinson, P. & Macdonald, D.I.M. 2019. Eocene–Recent drainage evolution of the Colorado River and its precursor: an integrated provenance perspective from SW California. *In*: Corbett, P.W.M., Owen, A., Hartley, A.J., Pla-Pueyo, S., Barreto, D., Hackney, C. & Kape, S.J. (eds) *River to Reservoir: Geoscience to Engineering*. Geological Society, London, Special Publications, **488**. First published online January 31, 2019, https://doi.org/10.1144/SP488-2019-272

Oliveira, E.C., Pla-Pueyo, S. & Hackney, C.R. 2018. Natural and anthropogenic influences on the Nhecolândia wetlands, SE Pantanal, Brazil. *In*: Corbett, P.W.M., Owen, A., Hartley, A.J., Pla-Pueyo, S., Barreto, D., Hackney, C. & Kape, S.J. (eds) *River to Reservoir: Geoscience to Engineering*. Geological Society, London, Special Publications, **488**. First published online December 10, 2018, https://doi.org/10.1144/SP488.5

Owen, A., Nichols, G.J., Hartley, A.J., Weissmann, G.S. & Scuderi, L.A. 2015. Quantification of a distributive fluvial system: the Salt Wash DFS of the Morrison Formation, SW USA. *Journal of Sedimentary Research*, **85**, 544–561, https://doi.org/10.2110/jsr.2015.35

Owen, A., Hartley, A.J., Weissman, G.S. & Nichols, G.J. 2016. Understanding fluid flow at a basin scale in fluvial reservoirs. Abstract presented at the Rain, Rivers and Reservoirs Geological Society Meeting, 27–30 September 2016, Edinburgh, UK, https://www.geolsoc.org.uk/~/media/shared/documents/Events/Past%20Meeting%20Resources/RRR%20conference/RRR%20abstract%20book.pdf (published as Uranium distribution as a proxy for basin-scale fluid flow in distributive fluvial systems. *Journal of the Geological Society, London*, **173**, 569–572, 2016, https://doi.org/10.1144/jgs2016-007).

Owen, A., Ebinghaus, A., Hartley, A.J., Santos, M.G.M. & Weissmann, G.S. 2017. Multi-scale classification of fluvial architecture: an example from the Palaeocene–Eocene Bighorn Basin, Wyoming. *Sedimentology*, **64**, 1572–1596. https://doi.org/10.1111/sed.12364

Patidar, S., Allen, D., Haynes, R. & Haynes, H. 2018. Stochastic modelling of flow sequences for improved prediction of fluvial flood hazards. *In*: Corbett, P.W.M., Owen, A., Hartley, A.J., Pla-Pueyo, S., Barreto, D., Hackney, C. & Kape, S.J. (eds) *River to Reservoir: Geoscience to Engineering*. Geological Society, London, Special Publications, **488**. First published online December 18, 2018, https://doi.org/10.1144/SP488.4

Reesink, A. 2016. Cambrian rivers and floodplains: the significance of microbial cementation, groundwater and aeolian sediment transport. Abstract presented at the Rain, Rivers and Reservoirs Geological Society Meeting, 27–30 September 2016, Edinburgh, UK, https://www.geolsoc.org.uk/~/media/shared/documents/Events/Past%20Meeting%20Resources/RRR%20conference/RRR%20abstract%20book.pdf

Reeves, H., Balmforth, H. & Lisk, I. 2015. UK's Natural Hazards Partnership (NHP). Abstract presented at the 1st Rain, Rivers and Reservoirs Meeting, 1–3 September 2015, São Paulo, Brazil, available at https://researchportal.hw.ac.uk/en/publications/rain-rivers-reservoirs-conference-sao-paulo-brazil-abstract-bookl

Russell, C.E., Mountney, N.P., Hodgson, D.M., Colombera, L. & Thomas, R.E. 2016. The complex shapes of fluvial meanders and the distribution of heterogeneity in point-bar deposits. Abstract presented at the Rain, Rivers and Reservoirs Geological Society Meeting, 27–30 September 2016, Edinburgh, UK, https://www.geolsoc.org.uk/~/media/shared/documents/Events/Past%20Meeting%20Resources/RRR%20conference/RRR%20abstract%20book.pdf

Silva, B. 2015. Inflows projections under conditions of climate change based on Eta atmospheric model dynamic downscaling: case study for hydroelectric power plants of São Francisco river basin. Abstract presented at the 1st Rain, Rivers and Reservoirs Meeting, 1–3 September 2015, São Paulo, Brazil, available at https://researchportal.hw.ac.uk/en/publications/rain-rivers-reservoirs-conference-sao-paulo-brazil-abstract-bookl

Simmons, J. 2015. Water and energy industry. *Geoscientist Online*, November, 10–15, https://www.geolsoc.org.uk/Geoscientist/Archive/November-2015/Water-in-the-energy-industry

Sinclair, H., Stuart, F., McCann, L. & Tao, Z. 2016. Cosmogenic nuclide concentrations in Neogene rivers of the Great Plains reveal the evolution of fluvial storage and recycling. Abstract presented at the Rain, Rivers and Reservoirs Geological Society Meeting, 27–30 September 2016, Edinburgh, UK, https://www.geolsoc.org.uk/~/media/shared/documents/Events/Past%20Meeting%20Resources/RRR%20conference/RRR%20abstract%20book.pdf

Skelton, L. 2015. Tyne after Tyne: reconnecting river pasts with presents and futures, 1530–2015. Abstract presented at the 1st Rain, Rivers and Reservoirs Meeting, 1–3 September 2015, São Paulo, Brazil, available at https://researchportal.hw.ac.uk/en/publications/rain-rivers-reservoirs-conference-sao-paulo-brazil-abstract-bookl

Stow, D.A.V., Nicholson, U., Kearsey, S., Tatum, D., Gardiner, A.R., Ghabra, A. & Jaweesh, M. 2016. The Euphrates river system: Pliocene to recent sediment facies, architecture and evolution. Abstract presented at the Rain, Rivers and Reservoirs Geological Society Meeting, 27–30 September 2016, Edinburgh, UK, https://www.geolsoc.org.uk/~/media/shared/documents/Events/Past%20Meeting%20Resources/RRR%20conference/RRR%20abstract% 20book.pdf

Ventra, D. & Clarke, L.E. (eds). 2018. *Geology and Geomorphology of Alluvial and Fluvial Fans: Terrestrial and Planetary Perspectives*. Geological Society, London, Special Publications, **440**, https://doi.org/10.1144/SP440.16

Wang, J. 2016. Fluid mixing process in a shallow natural lake. Abstract presented at the Rain, Rivers and Reservoirs Geological Society Meeting, 27–30 September 2016, Edinburgh, UK, https://www.geolsoc.org.uk/~/media/shared/documents/Events/Past%20Meeting%20Resources/RRR%20conference/RRR%20abstract%20book.pdf

Weissmann, G.S., Hartley, A.J., Nichols, G.J., Scuderi, L.A., Olson, M.E., Buehler, H. & Banteah, R. 2010. Fluvial form in modern continental sedimentary basins: distributive fluvial systems. *Geology*, **38**, 39–42, https://doi.org/10.1130/G30242.1

Whateley, M.K.G. & Pickering, K.T. (eds). 1989. *Deltas: Sites and Traps for Fossil Fuel*. Geological Society, London, Special Publications, **18**, https://doi.org/10.1144/GSL.SP.1989.041.01.24

Xia, X. & Liang, Q. 2016. A new high-performance depth-averaged modelling framework for flow-like landslides. Abstract presented at the Rain, Rivers and Reservoirs Geological Society Meeting, 27–30 September 2016, Edinburgh, UK, https://www.geolsoc.org.uk/~/media/shared/documents/Events/Past%20Meeting%20Resources/RRR%20conference/RRR%20abstract%20book.pdf

Yeste, L.M., Henares, S., McDougall, N., García-García, F. & Viseras, C. 2018. Towards the multi-scale characterization of braided fluvial geobodies from outcrop, core, ground penetrating radar and well log data. *In*: Corbett, P.W.M., Owen, A., Hartley, A.J., Pla-Pueyo, S., Barreto, D., Hackney, C. & Kape, S.J. (eds) *River to Reservoir: Geoscience to Engineering*. Geological Society, London, Special Publications, **488**. First published online November 28, 2018, https://doi.org/10.1144/SP488.3